Applied Thermal Engineering 65 (2014) 124–134

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Optimization and comparison of double-layer and double-side micro-channel heat sinks with nanofluid for power electronics cooling

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HIGHLIGHTS

- Microchannels are integrated inside the Cu-layer of direct bond copper.
- The double-layered and sandwich microchannel structures are comparatively studied.
- Optimized geometry and design is obtained based on parametric studies.
- Water based Al_2O_3 nanofluid is investigated for the microchannel cooling.

ARTICLE INFO

Article history:
Received 5 September 2013
Accepted 4 January 2014
Available online xxx

Keywords:
CFD
Direct bond copper
Micro-channel heat sink
Nanofluid
Power electronic cooling

ABSTRACT

The tendency of increasing power rating and shrinking size of power electronics systems requires advanced thermal management technology. Introduction of micro-channel heat sink into power electronics cooling has significantly improved the cooling performance. In present work, two advanced micro-channel structures, i.e. double-layer (DL) and double-side (sandwich) with water as coolant, are optimized and compared by computational fluid dynamics (CFD) study. The micro-channels are integrated inside the Cu-layer of direct bond copper (DBC). The effects of inlet velocity, inlet temperature, heat flux are investigated during geometry optimization. The major scaling effects including temperature-dependent fluid properties and entrance effect are considered. Based on the optimal geometry, the sandwich structure with counter flow shows a reduction in thermal resistance by 59%, 52% and 53% compared with single-layer (SL), DL with unidirectional flow and DL with counter flow respectively. Water based Al_2O_3 (with concentration of 1% and 5%) nanofluid is further applied which shows remarkable improvement for wide channels.

1. Introduction

With the further increasing demands on high temperature power electronics systems, like hybrid electric vehicles (HEV) and aerospace applications, the conventional packaging and cooling technologies become hard to meet the demands. The standard power electronics packaging normally consists of multiple thermally resistive layers. The long heat conduction path and thermal interface materials (TIM) with low thermal conductivity (typically 0.5–3 W/K m) degrade the cooling performance significantly. The conventional cooling technologies, including natural air convection and forced air convection, have become hard to cool the high heat flux ($\geq$100 W/cm^2).

Some early works on advanced packaging and cooling technologies included: replacement of TIM with solder between DBC (direct bond copper) and heat sink [1], double-side cooling with heat pipes [2] or liquid impingement cooling [3]. The micro-channel heat sink (MCHS) exhibits great potential in power electronics cooling since the first fabrication by Tuckerman and Pease, which cooled a heat flux of 790 W/cm^2 with a temperature rise of 71 °C [4]. The DBC with a sandwich structure of Cu-ceramic-Cu plays a key role in the modularization and integration of power electronic systems. It serves as the mechanical support, electrical isolation, interconnection and heat removal path for the power module. With integration of micro-channels inside DBC, the cooling performance is ultimately improved by minimizing heat conduction path and completely eliminating TIM. The MCHS can be either

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http://dx.doi.org/10.1016/j.applthermaleng.2014.01.005

Nomenclature

A	area (m^2)
Br	Brinkmann number
c_p	specific heat (J/kg K)
D_h	hydraulic diameter (m)
f	Fanning friction factor
Gz	Graetz number
h	heat transfer coefficient (W/K m^2)
H	height (m)
k	thermal conductivity (W/K m)
l	length (m)
M	Maranzana number
N	number of micro-channels
Nu	Nusselt number
Δp	pressure drop (Pa)
P_{pump}	pumping power (W)
Pr	Prandtl number
q	heat flux (W/cm^2)
R_{cap}	capacitive thermal resistance (K/W)
R_{conv}	convective thermal resistance (K/W)
R_{cond}	conductive thermal resistance (K/W)
Re	Reynolds number
t	thickness (m)
T	temperature (K)
U	velocity vector (m/s)
u, v, w	flow velocity (m/s)
W	width (m)
x, y, z	Cartesian coordinates

Greek symbols

α	aspect ratio
β	width ratio
δ	thickness of interfacial layer
η	fin efficiency
$k(\infty)$	Hagenbach factor
μ	viscosity (N s/m^2)
ρ	density (kg/m^3)
ϕ	viscous dissipation
φ	volumetric concentration of nanoparticles

Subscripts

app	apparent
av	average
ch	channel
eff	effective
f	fluid
j	junction
inf	inletnanofluid
o	outlet
s	solid

fabricated in the back Cu-layer of DBC [5–7] or in the AlN-layer of DBC [8–10].

The analytical model considering the heat transfer and fluid dynamics of MCHS needs to be developed in order to facilitate geometry design. Some of the early works used 2D simplified model to build the correlation for thermal resistance [11–13]. Hwang et al. [11] enhanced the performance of MCHS for both deep-channel and shallow-channel cases by increasing flow rate which reduced caloric resistance. Knight et al. [12] analytically described the optimization scheme for the earlier works including Tuckerman and Pease (1981) and Goldberg (1984) by varying both fin and channel, the latter was fixed previously. Weisberg et al. [13] numerically analyzed the conjugate heat transfer and presented the design algorithm for the selection of the channel size.

At a later time, 3D conjugated heat transfer model was developed to analyze flow and simulate heat transfer performance of MCHS [14–23]. Lee and Garimella [15] proposed correlations for predicting Nusselt and average Nusselt number obtained by 3D numerical simulations for thermally developing flow with the aspect ratio (α) from 1 to 10. They concluded that both the local and average Nusselt number depends on the dimensionless axial distance and α. Chein and Chen [16] numerically investigated the performance of heat sink under 6 different inlet/outlet locations, others conditions were the same. Considering thermal resistance, overall heat transfer coefficient and pressure drop as the main criteria for heat sink fulfillment, it was found that U- and V-types showed better performance than other geometries. Gunnasegaran et al. [17] also numerically investigated the effect of three different channel shapes on heat transfer characteristics. They pointed out that the Poiseuille number as well as heat transfer coefficient augmented with increasing Reynolds number. Under these conditions, the rectangular channels showed the best performance and followed by trapezoidal and triangular. Kim [18] summarized two analytical models and 3D numerical approach. Then the data of two analytical models which included the fin model and porous medium model were compared with numerical simulation. The optimal values of channel height, width and fin thickness under the constraint of maximum pumping power were obtained. Husain and Kim [19] performed the optimization of MCHS with the help of surrogate analysis and hybrid multi-objective evolutionary approach. Ambatipudi and Rahman [20] varied the channel depth, width, number and flow rate. The results were compared with the experimental works of Harms [21] and Harms et al. [22]. Li and Peterson [23] determined the optimal parameters under a constant pumping power of 0.05 W which were found at channel number $N = 100$, channel width ratio $\beta = 0.6$ and channel aspect ratio $\alpha = 12$. They provided a fully understanding influence of the optimized spacing and channel dimensions on heat transfer capacity of MCHS.

As the channels shrink to micro-size, the well-established theories and analytical correlations for the macro-channel are no longer suitable. By comparing Nusselt number at constant and variable properties, Herwig and Mahulikar [24] concluded that the temperature dependence of thermo-physical properties are important with scaling effects and cannot be negligible in micro-size channels. Li et al. [25] numerically compared inlet, average and variable properties for laminar flow in rectangular channels and made the conclusion that variable properties were more accurate in terms of engineering application. Entrance effect should also be taken into account. Qu and Mudawar [26] numerically analyzed 3D fluid flow and heat transfer characteristics in rectangular MCHS. They found the highest heat flux and Nusselt number at inlet while zero in the corners. Lee et al. [27] experimentally investigated heat transfer with hydraulic diameters ranged from 318 to 903 μm. These results had wide disparities with conventional correlations. The effect of viscous dissipation in terms of Brinkman number was studied by Tso and Manulikar [28]. They elaborated Brinkman number for correlating the convective heat transfer in MCHS. Morini and Spiga [29] demonstrated that channel aspect ratio, Brinkman number and Reynolds number were